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HOT GAS RECIRCULATION MEASUREMENTS ON FOUR DIFFERENT-SIZE MODELS OF A SIMPLE VTOL CONFIGURATION

Dr.-Ing. R. Jenny

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FORMULA DESIGNATIONS

q	dynamic pressure or $P - p$
P	total pressure
p	static pressure
D	diameter
B	width of the wind tunnel
g	acceleration of gravity
h	distance from the platform
$\dot{m}$	mass flow per second
x	distance from the jet exhaust in the axial direction
T	absolute temperature
Δt	temperature difference $t - t_U$(°C)
V	flow velocity
β	flight velocity
	coefficient of expansion of air
κ	contraction ratio

INDICES

A	exhaust of the engine
E	intake of the engine
U	surroundings
∞	condition at infinity

HOT GAS RECIRCULATION MEASUREMENTS ON FOUR DIFFERENT-SIZE MODELS OF A SIMPLE VTOL CONFIGURATION

Dr.-Ing. Rudolf Jenny(1)

ABSTRACT. Investigation of the influence of the size of the wind tunnel and the temperature of the jet stream on the recirculation behavior of a VTOL configuration. It is found that the relationship between the sizes of the wind tunnel and the VTOL model is quite critical. (A68-39212)

SUMMARY

For jet-supported VTOL aircraft, the investigation of recirculation behavior is an important problem which has been solvable only through model experiments. /1*

The experimental technique which is used in such studies is well known, but a number of questions still remain open. In view of the signficance of such investigations, they deserve our full attention.

This work reports on measurement with a simple VTOL configuration. It has as its subject the effect of the wind tunnel size and the jet temperature on recirculation. The means by which this study was planned and carried out can be traced back to a series of measurements by which the transition of a VTOL model was studied in a wind tunnel.

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* Numbers in the margin indicate the pagination in the original foreign text.

(1) Experimental and Research Station, Federal Aircraft Plant, Emmen, Switzerland.

The completed investigation produced the following results:

The size of the model in proportion to that of the wind tunnel can have a destructive effect on the accuracy of the measurements, because when the model is too large the flow field cannot be simulated properly. Thus, with large models the dynamic pressure ratio must be limited so that the direct jet always lies clearly within the wind tunnel. Data on the allowable jet diameter are provided.

The magnitude of the exhaust temperature of the simulated jet engine has not only an effect on the far field of the recirculation, but also on the near field. High jet temperatures produce a stronger mixing of the jet with the cold surroundings, so that along with the mixing temperature, the dynamic pressure also falls more rapidly than with a cold jet. In many cases, experiments carried out with low temperatures could have led to previous pessimistic results.

INTRODUCTION

The possibility of a jet-supported takeoff and landing of VTOL aircraft was provided by the development of powerful jet engines. Unfortunately, this principle has some fundamental difficulties, i.e., the highly undesirable side effects of the jet, such as:

-- induced aerodynamic loss of lift.
-- hot gas recirculation
-- ground erosion

These side effects of the propulsive jet can be of such significance for the study of a project that the most accurate data possible are needed even in a very early stage. Since the magnitude of these effects is strongly dependent on the arrangement of the engine and the form of the aircraft (supporting surfaces, engine intake, etc.), these data are provided freshly for each new project configuration. Thus, it appears necessary to investigate these effects with small models in a wind tunnel.

In the following we will be concerned with the problems of such wind tunnel experiments, and will be limited to the carrying out of recirculation measurements.

We know from the classical model-experiment technology that model experiments are possible at all only because certain flow processes are not dependent on the dimensions of the body through or around which the stream flows, and because physically similar effects (e.g., forces) arise for different sizes of models. It appears that the model dimensions or one of the magnitudes of the process may not be changed arbitrarily without changing the character of the streaming. One considers only the Reynolds number or the Mach number. For large, relatively sharply bounded regions of these numbers it is fortunately possible to view the streaming processes as similar. The practical consequence of this is that not all the characteristic quantities need be the same simultaneously in the model and performance. This freedom is the first hypothesis for useful model experiments with tolerable expense. For studies with jet-supported VTOL aircraft this model law naturally applied for the usual investi- /2
gations. The circumstances are complicated by the presence of the hot, turbulent gas jet of the lifting engine insofar as the proper simulation of t the streaming fields depends on that of the temperature fields.

In England, where hot gas recirculation measurements with models were carried out quite early, the interested firms, together with the National Gas Turbine Establishment (NGTE), have carried out the principal type of investigations on the important model laws [2]. In spite of this basic work, it appears that the question is not yet entirely answered — whether the jet temperature for such experiments must be simulated at the true magnitude, or whether temperatures of 200 to 300°C are sufficient. Part of the current work is concerned with this question, and attempts to show new results.

With conventional model experiments we know further what effect the size of the wind tunnel has on the results. Thanks to a thorough knowledge of the flow mechanisms, we can in this classical case calculate transfer corrections for the performance magnitudes. We lack this understanding of the processes

in recirulation studies, so that the test engineer has no guidelines for the choice of an allowable model size for his tunnel. This work will attempt to provide some guiding principles for that.

STATEMENT OF THE PROBLEM

Since various VTOL aircraft projects are already in the flight test stage, it is possible to compare the older wind tunnel measurements with flight measurements. In this way, some highly valuable knowledge could be gathered, so that it is now considered known, how recirculation measurements must be carried out. Still, this very limited knowledge does not change the fact that our knowledge of the actual processes is not very complete. This is seen in the fact that there is still no useful mathemat cal model by which recirculation may be calculated for even simple models. Thus, a project team is still assigned for a long time exclusively to the carrying out of wind tunnel experiments. This seems to us to justify further efforts to perfect the test technique.

We will select two from the catalog of more or less solved questions. They are these:

- -- Investigation of the allowable model size for a given wind tunnel.
- -- Effect of the jet temperature on the recirculation.

These effects should be studied with the simplest possible test apparatus. For this, it was appropriate to use the simplest VTOL configuration, i.e., an isolated jet engine with thrust perpendicular to the ground. Since both problems are grounded in the impulse effect of the jet, this configuration appears to fulfill the most important requirements. It has the advantage that the so-called "upwash" which is often decisive for the recirulation in multiple-jet configurations does not exist. Thus, the effects which are sought stand out clearly.

A further advantage, not to be underestimated, for this configuration is the simple, easily viewed flow condition.

On the other hand, the very small recirulation of this arrangement presents a disadvantage for the measuring technology. We attempted to correct for it somewhat by the choice of the small distance from the ground, $h/D_A = 1.25$.

The process of takeoff or landing can be divided into two phases. The first begins with the starting of the reactor and ends with a still small forward velocity, somewhat characterised by the dynamic pressure ratio q_A/q_∞ of 10,000. In this phase, recirculation measurements are usually carried out with stationary models without thrust.

The second phase includes the higher flight velocities and must be investigated on moving models or in the wind tunnel.

While the English measurements generally dealt with the first phase, the measurements carried out here correspond to the problem of the second phase.

We will not discuss here the question of which of the two techniques, moving the model or thrust in a wind tunnel, should be given the advantage. The measurements described below were made exclusively in the wind tunnel and with a stationary platform. We do not believe that the stationary platform affected the results of this study significantly.

Effect of the Model Size. In order to investigate the effect of various sizes of the jet diameter on recirculation, four different model engines were prepared. Their sizes were in the ratio of 1:2:3:4. The investigation was carried out in two wind tunnels of different sizes. From these we obtained the following ratios of half-tunnel-width to jet diamter, $B/2D_A$:

D_A(mm)	20	40	60	80
Tunnel 2.4 x 1.7m	60	30	20	15
Tunnel 7 x 5m	--	--	58	44

Effect of Jet Temperature. The effect of various jet temperatures on the recirulation were investigated with the same configuration, but with one jet diameter D_A and with one example of the dynamic pressure ratio q_A/q_∞. The available combustion chamber allowed heating of the air to simulate jet temperatures between 200°C and 1000°C. The jet velocity corresponded to a dynamic pressure of $q_A = P-p = 450\ kg/m^2$ = constant.

EXPERIMENTAL ARRANGEMENT

The chosen simple VTOL configuration consisted basically of a single simulated jet engine. Figure 1 shows the construction of the model in cross section. With a vertical tube, compressed air was blown through a nozzle with a contraction ratio of $\kappa = 1.28$. A jet combustion chamber in series allowed the air temperature to be changed within wide limits. The engine-like cowling which was intended to simulate somewhat the exterior contour of a jet engine was made of ceramic and at its upper end formed the intake for our model engine. Through this intake, with the help of a suction tube arranged concentrically with the exhaust duct, air could be drawn off and the sinking action of the engine could be simulated. Some of the experiments were planned with very high temperatures, so the components at the outlet side of the combustion chamber had to be made of nonflammable materials. Excessive cooling of the air before exit from the nozzle was prevented by double-wall construction of the inner feed duct. Because of this isolation, a relatively "complete'' temperature profile could be obtained.

The platform was assembled from 2 mm thick sheet iron plates. The plates rested on folded profiles about 30 cm above the actual tunnel floor. By such construction, effective cooling of the hot portion of the platform was

attained by means of the tunnel air. This likewise reduced to a minimum the obstruction of the wind tunnel.

Special precautions were needed in order to prevent warping of the platform due to the occasionally great temperature gradients. For this purpose a plate of stainless steel with the dimensions 40 x 40cm was inset into the platform directly below the nozzle. It was placed only loosely and was provided with a peripheral clearance of about 0.5 mm.

During the investigation with high temperatures it appeared that a further division of this plate was necessary in order to prevent deformation due to heat stress at the edge. In the center of the innermost plate, i.e., perpendicularly under the axis of the nozzle, were the total pressure and temperature measuring points which allowed measurement of the jet parameters. This simple /4 measuring arrangement was possible because of the small distance from the platform, so that the measuring equipment was still located in the nucleus of the jet. For exact measurement of the total pressure it must be noted that the probe would have to lie exactly at the stagnation point. For this purpose, four other pressure measuring points were arranged in a circle around this measuring point. This allowed aerodynamic centering in the jet.

The temperature of the air drawn off was measured by eight thermoelements distributed around the circumference of the input lip. For simplicity, not the temperatures of the individual measuring points but their arithmetic mean is designated as the recirculation and illustrated in the diagrams.

In the choice of the thermoelements, particular attention was paid so that they would follow the temperature of the drawn off air with minimum lag. This was attained by the choice of very thin, nontwisted 0.1 mm constantan-nickel elements, which were welded with as little "bead" at the end as possible. The ambient or tunnel temperatures were also measured by means of the same type of thermoelements. Here in particular it appeared to be of the utmost importance for the thermoelements to have a small time constant, so that, with the small flow velocities in the wind tunnel, the ambient temperature could be measured practically without delay.

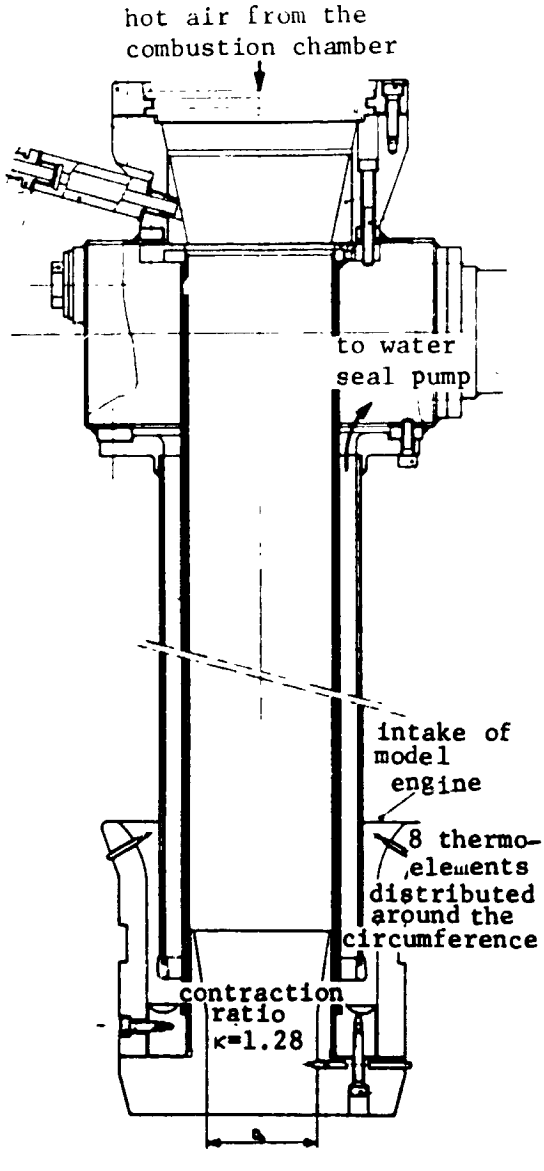

Figure 1. Section through the engine model.

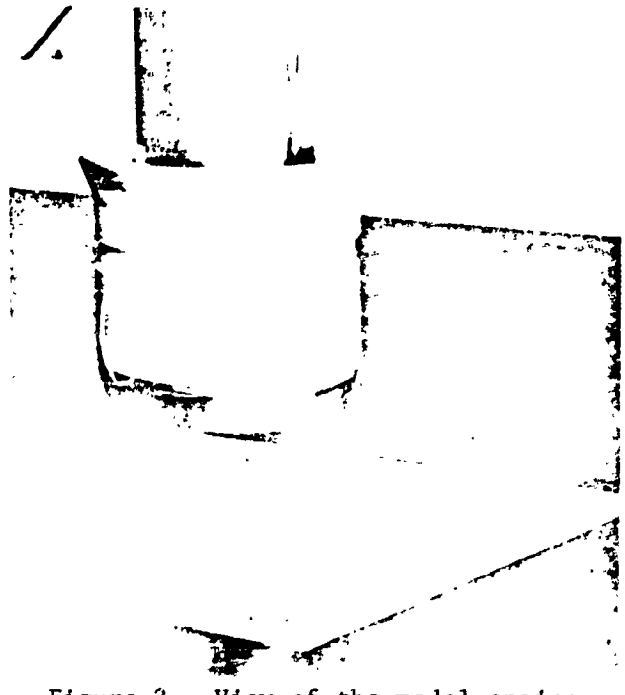

Figure 2. View of the model engine.

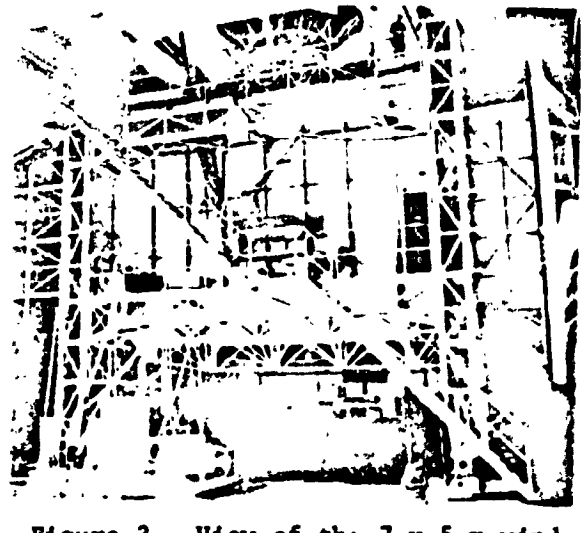

Figure 3. View of the 7 x 5 m wind tunnel.

Measurement of the drawn off and exhausted air masses was performed with the help of two identical measuring sections built into the corresponding duct systems. The two flow rates were brought into agreement.

We carried out the entire experimental series with a mass ratio $\dot{m}_A/\dot{m}_E = 1$, where $\dot{m}_A$ signifies the air mass entering the combustion chamber. We held as accurately as possible at the actual conditions, although earlier measurements have shown that a deviation of $\pm$ 50% have no significant effect on the recirculation.

The measurements were made in both of the subsonic wind tunnels of the Emmen Aircraft Plant. The small wind tunnel has a closed cycle, but an open measuring section with a cross section of 2.4 x 1.75 m. The large wind tunnel of 7 x 5 m (see Figure 3), in which velocities up to 80 m/sec are possible, was used for this study with the closed measuring section. Figure 4 shows the test equipment built into the large wind tunnel.

The temperatures were measured with a digital data acquisition system. Of the 100 measuring points available , 15 were used for this investigation. Figure 5 shows the data acquisition system in its present assembly. An integrating voltmeter provided a time average of the continuous measuring signal. The arbitrarily adjustable integration time allowed matching the measuring apparatus to the frequency content of the measuring signal.

Due to the extremely sensitive voltmeter and the well defined time-averaging through integration of the measuring signal, good accuracy and reproducibility are attained.

PRELIMINARY EXPERIMENTS

Looking toward the comparison of the recirculation measurements for the four different large models, the mixing properties of the four jets were investigated in a preliminary experiment.

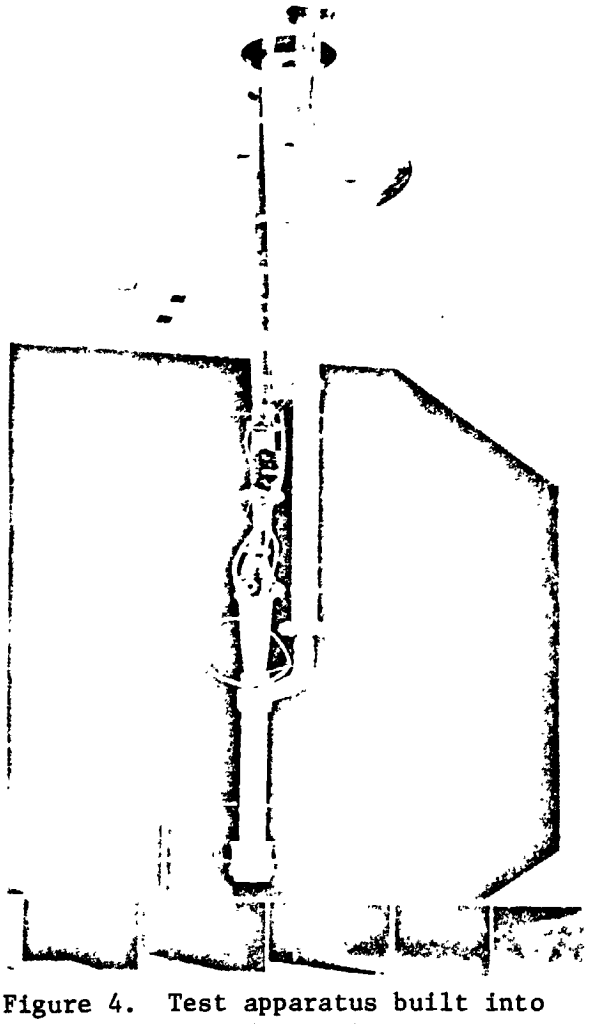

Figure 4. Test apparatus built into the 7 x 5 m wind tunnel.

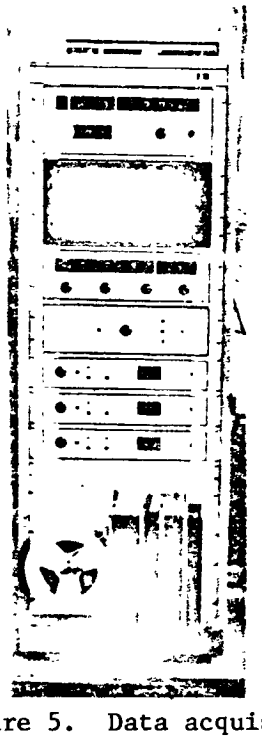

Figure 5. Data acquisition system, Vidar 5202 D-DAS with integrating digital voltmeter.

It appeared to us to be of less significance that the velocity profile and with it the mixing properties corresponded exactly with the theoretical ones or with those of a certain engine, than that they demonstrated such highly similar ratios among themselves. /6

These studies were done with the free jets of the four nozzles in quiet air. Figure 6 shows the velocity profile for a cold jet at a short distance from the nozzle $x/D_A = 0.37$.

The four velocity profiles show only slight deviations, which apparently derive from the different magnitude of the boundary layer component in the four jets. These differences could have been diminished still more with a

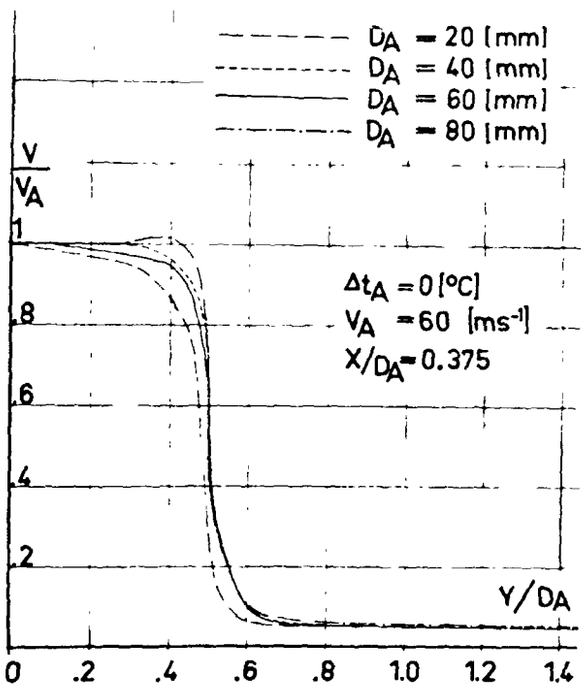

Figure 6. Velocity profiles at the exhaust of the four model engines.

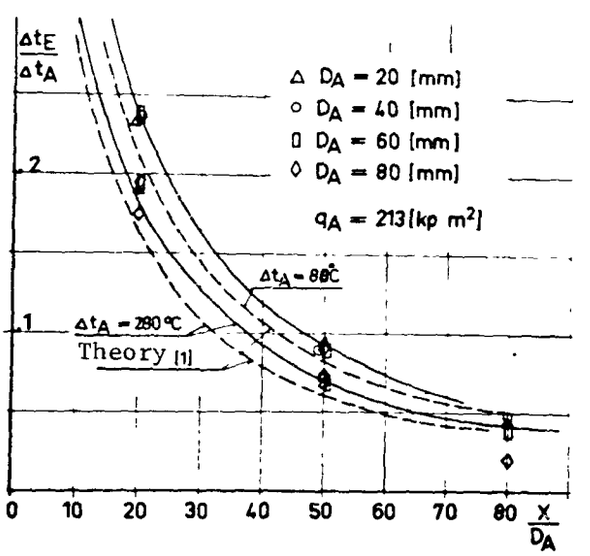

Figure 7. Comparison of the jet mixing for the four nozzles. (Temperature curve along the jet axis).

somewhat higher contraction κ. With that, the same mixing properties could have been expected for all four nozzles. In order to demonstrate this, the air jet was heated and the temperature drop on the jet axis measured. Figure 7 shows the jet temperature along the axis for the four jets and two different exhaust temperatures Δt_A of 80°C or 280°C. Further measurements have shown that the absolute magnitude of the jet velocity has a small effect on these mixing properties. The results presented in Figure 7, can be considered as representative for velocities between 30 and 120 m/sec.

On the other hand, one sees from this result that the height of the jet temperature at the exhaust exerts an effect on the maximal temperature in a section x/D_A. This property of hot jets is well known. A semi-empirical theory which allows the temperature course to be calculated for a simple circular jet can be found in the work of Abramovich [1]. The dashed curves in Figure 7 represent the temperature course calculated by this theory.

This result appears significant to us. We will return again to this result later.

We conclude from the results of this preliminary experiment that the four model engines give geometrically similar free jets with the same mixing properties at the same jet temperatures, with adequate accuracy. This offers the guarantee that differences in recirculation in the measurement of wind tunnel effects must derive from the size ratios and not be grounded in the jets themselves.

RESULTS

Effect of the Size of the Wind Tunnel.

The first measurements with the four different sizes of models were done in the small wind tunnel. Figure 8 shows the recirculation obtained with them. Both of the small models (jet diameter D_A = 20 mm or 40 mm) gave approximately the same results in the major portion of the region of dynamic pressure ratios which were investigated. In contrast, both the larger models show strong deviations, which can in no way be explained by the measuring apparatus. It was an obvious assumption that in this case it was due to the effect of a too-small wind tunnel. Testing of the outermost limits of the basic /7 jet strengthened this assumption. It could be shown that for those dynamic pressure ratios q_A/q_∞ at which the divergence in the results began, the basic jet limit (vortex line) had extended into the wind tunnel nozzle, and laterally far from the model engine and out of the region of the wind tunnel flow. The flow field was strongly falsified because of it, and appeared to significantly influence the mixing of the engine air with the surrounding air. Figure 9 shows the approximate position of these limits.

Because of this further studies were planned, in which the two large models were to be tested in a large wind tunnel. Figure 10 presents the results obtained. Now the measured recirculations correspond very well with those obtained with the two small models in the small wind tunnel.

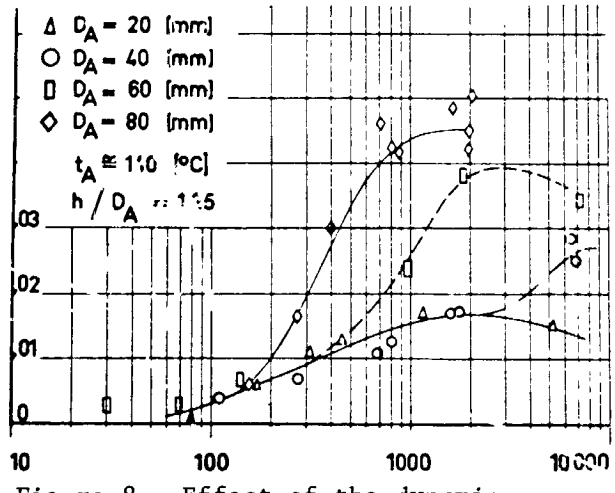

Figure 8. Effect of the dynamic pressure ration q_A/q_∞

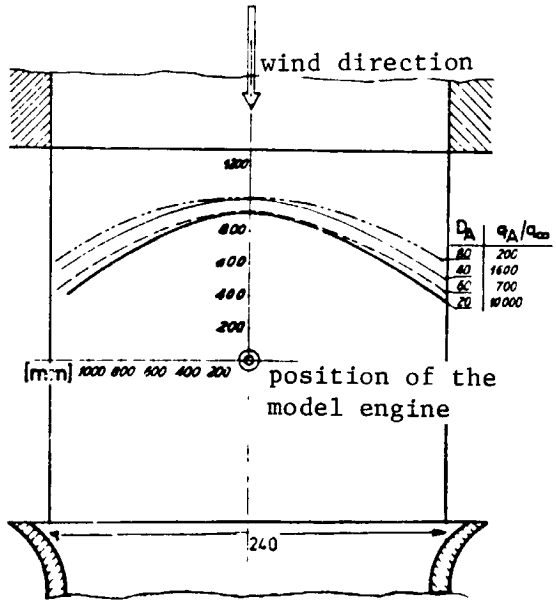

Figure 9. Most advanced allowable position of the vortex line.

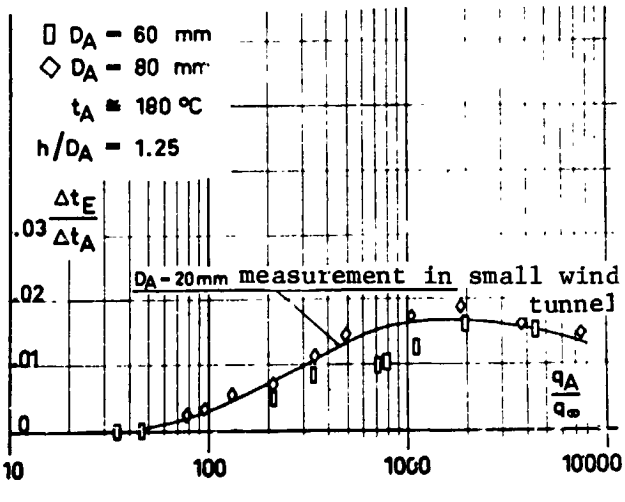

Figure 10. Effect of the dynamic pressure ratic q_A/q_∞

From these results, one can attempt to determine the allowable jet diameter for a given wind tunnel It is clear that D_A depends on the range of dynamic pressure ratios, q_A/q_∞ to be studied. Figure 11, shows the limits determined in the small tunnel with the 80, 60, and 40 mm nozzles. The smallest model engine is not critical in the region studied, as could be assumed on the basis of the expansion of the direct jet.

This result was obtained in the case of a single, freely mounted model engine, and must be converted with care for other jet arrangements. Colin [4], has published flow diagrams of the direct jets for various simple jet arrangements.

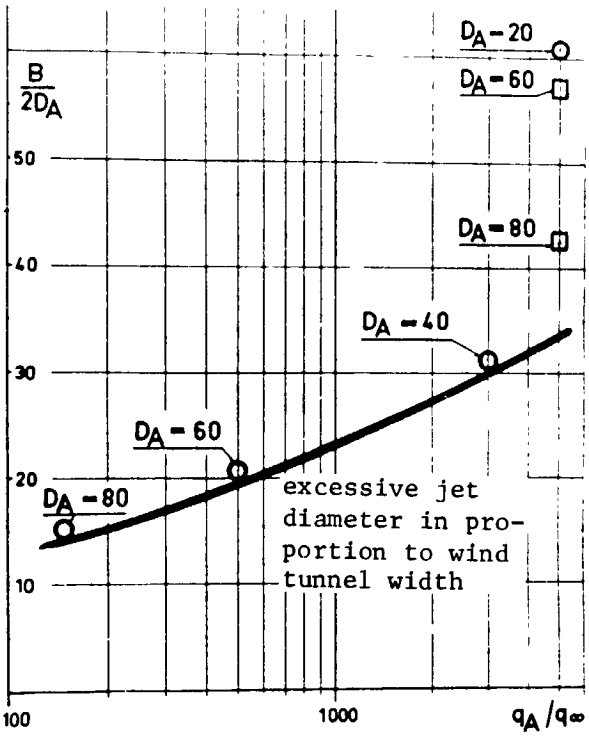

Figure 11. Dependence of the allowable wind tunnel width on the dynamic pressure ratio.

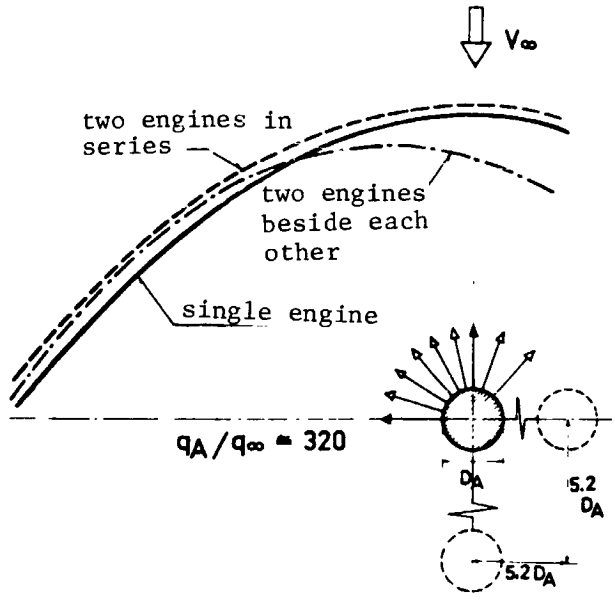

Figure 12. Comparison of the expansion of the direct jet for different engine arrangements.

Figure 12 summarizes the limits of the direct jets which are produced by /8 an engine which is used alone, beside, or following a second engine. The spreading of these direct jets in the directions in which they are not perturbed by the second jet is hardly different. This condition allows the results of our investigation to be applied also to other jet arrangements.

For very exact measurements or jet arrangements which are difficult to consider, it might be recommended that the course of the jet boundary be determined by means of a preliminary experiment. With this, one can establish the region of dynamic pressure ratios q_A/q_∞ within which the experiments should be performed.

Effect of the Jet Temperature Δt_A

As early as 1964, Cox and Abbott [2], at the NGTE concerned themselves with the study of the effect of the jet temperature simulated in models on the recirulation measurements. In reference [3], Abbott came to the conclusion that simulation of dynamic pressures q_A/q_∞ as opposed to the velocity ratio V_A/V_∞ in an experiment yielded a too-low calculation of exhaust temperature. The deviations from this result, described in the following were first clear with very high temperatures.

On the other hand, in Reference [2], there are results described which were determined with a stationary direct jet and which show that the range of action of such a jet (range of action = distance from the ground stagnation point to the lifting of the jet from the ground) may be described approximately equally well in the function

$$(V_A^2/\beta g t_A D_A)\frac{T_U}{T_A}$$

or

$$V_A^2/\beta g t_A D_A$$

Both these parameters were determined from a simple analysis of the Archimedean lift on the direct jet. At times the entire effect of the jet temperature on the recirculation measurements was ascribed to this Archimedean lift. It was further concluded that on this basis the jet temperature t_A will have an effect only in the case where air from the far field is admitted into the engine intake. But now we appear to produce some results deviating from those described in the section "Preliminary Experiments".

The temperature drop along the axis of the horizontal free jet cannot be explained with the help of the Archimedean lift. This works only perpendicularly to the jet axis and produces only a slight upward curvature of the jet. In the investigations which were done, a scarcely detectable displacement of the temperature profile and velocity profile was observed with the velocities and nozzle distances used.

On the other hand, even with very small distances x/D_A there is a strong drop of the temperature in the jet axis in the case of the hot jet as compared with the less hot. From this one must conclude that the higher jet temperature has changed the mixing properties of the circular jet. The theoretical curves indicated in Figure 7, were calculated for the two jet temperatures t_A = 80°C or 280°C by means of the semi-empirical theory of Abramovich. Although the theoretical and experimental curves are somewhat displaced, the theory describes the phenomenon satisfactorily in the cases studied. Even here large difference arise for various high temperatures. Therefore, with a free jet not only the temperature field, but also the flow field itself is temperature-dependent.

This results suggested the conjecture that the same mechanism is effective in the case of a free jet turned toward the platform. In order to test this, the model engine was driven with variable and at times very high temperatures. For this study a constant dynamic pressure of 450 kg/m^2 was applied. The wind tunnel velocity was chosen relatively high, to give a dynamic pressure ratio /9 q_A/q_∞ of 560. This should have the effect that as much of the mixing as possible would go on near and in front of the engine. The pressure field generated by the Archimedean lift is negligibly small in this case in proportion to the pressure fields produced by the incident flow.

Figure 13 shows the results obtained from these experiments. One can see clearly the drop in the recirulation of about 30% in the case of the jet temperature of 800°C as opposed to 200°C.

With this it can be confirmed that the height of the jet temperature affects the recirculation also with VTOL configurations, where the effect of the Archimedean lift may be neglected. One must suppose that even with configurations in which the recirculation is determined by strong "up-streaming", the proper simulation of the exhaust temperature should be attempted, in order to simulate accurately the flow field as well as the temperature field.

Still further investigations with other VTOL configurations are necessary in order to say definitely how great the error to be expected may be. The

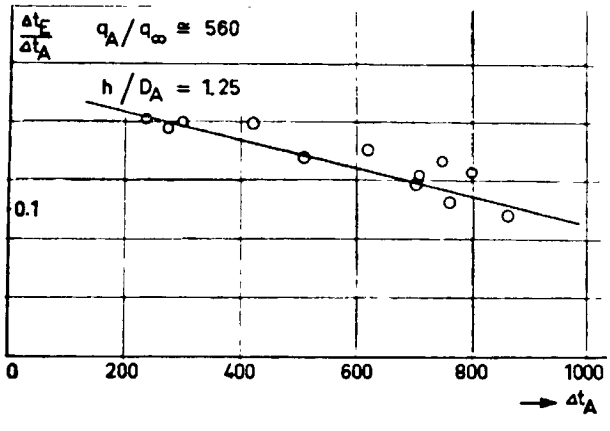

Figure 13. Effect of the jet temperature Δt_A.

VTOL configurations which we studied showed deviations of 30% for temperatures between 200°C and 1000°C. This is not serious for the present requirements for recirculation measurements.

The test engineer, nevertheless, should know about these effects so that he can determine from case to case whether it is important for his investigation to simulate the magnitude of the jet temperature properly.

The difficulties which arise for the construction of such a recirculation model are important. It would be desirable to produce jets through proper correction of other test parameters which would properly simulate not only the range of action, but also the temperature drop along a flow line. This could be attained, for example, if the jet diameter D_A was produced not entirely similar to the model, and additional small correction was assumed for the dynamic pressure ration q_A/q . It would have to be shown by further measurements whether these expedients, with jet temperatures between 200°C and 300°C would yield sufficiently accurate results, or whether in spite of all the problems it will be necessary to simulate the correct jet temperatures for the magnitude of the construction.

CONCLUSIONS

1. When recirculation measurements are carried out in a wind tunnel, it is necessary to consider that the flow conditions are not falsified by too large a model (engine diameters). For each case it is recommended that the spreading of the direct jet be estimated by means of the results provided here, or for complicated configurations, be determined directly in a preliminary experiment.

2. It would be desirable to maintain the correct jet temperature. The considerations employed indicate that only in this case can both the temperature field and the flow field be properly simulated. Since one of the causes is to be sought in the changed jet mixing, this applied not only for the field far from the engine but also at a distance of a few jet diamters.

Further investigations must be performed in order to clarify the practical significance of maintaining the proper jet temperature in model studies.

ACKNOWLEDGEMENTS

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